Status of C-Mod and Opportunities for Collaborative Experiments

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NSTX weekly meeting

January 30, 2006

C-Mod plasmas & parameters are ITER-like

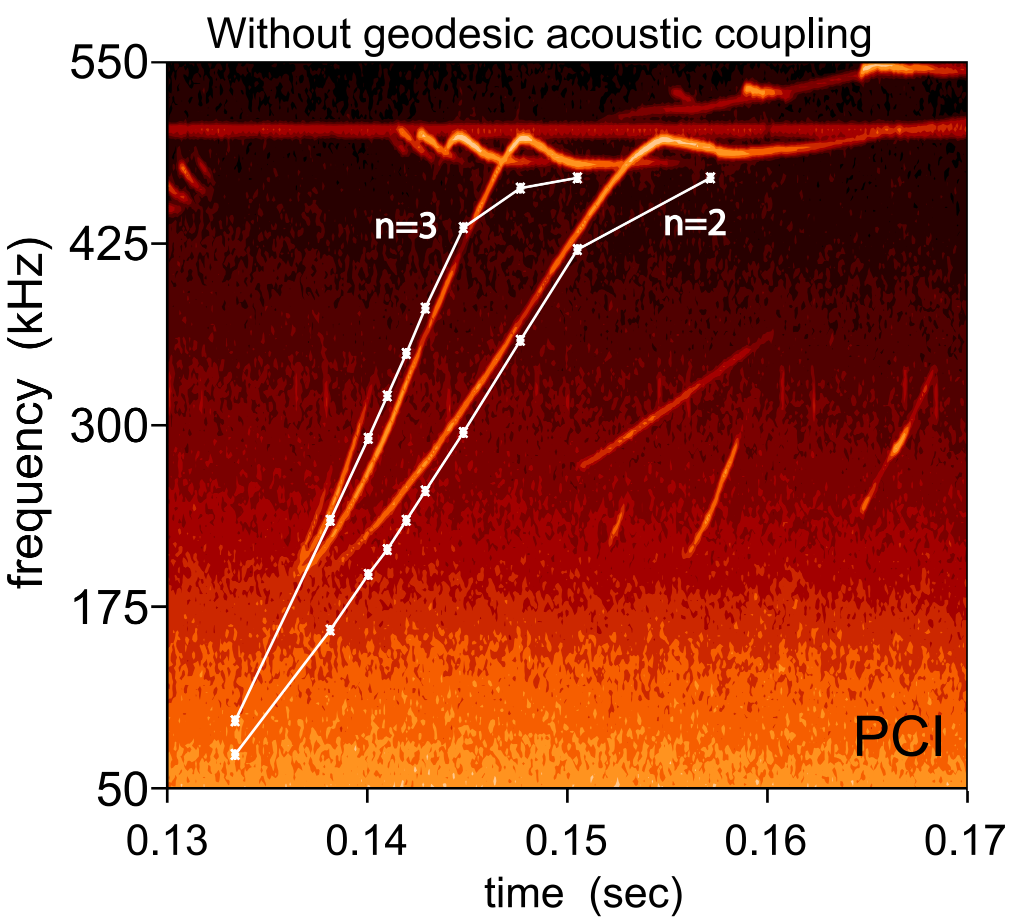
- ITER shape & divertor geometry
- High density Hmode is standard operating regime
- Ti = Te
- No external momentum input i.e. no beams
- Bt = 5.4 Tesla
- All metal walls … with ‘reversible’ boronization
- High divertor parallel heat flux (~0.5 GW/m^2)
- Divertor is opaque to Lyman-α, neutrals
- Pulse length is many L/R times.

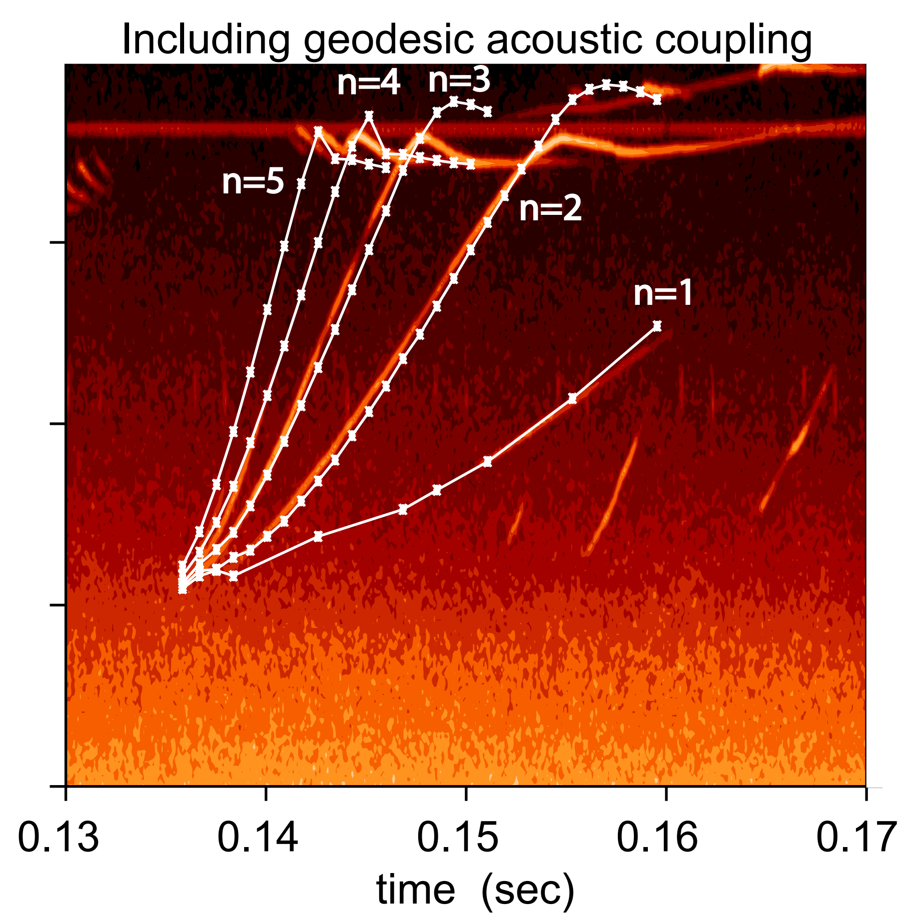
C-Mod Facility Features

- Heating and Current Drive
  - Reliable 6 MW ICRF, 40-80 MHz (D(H), D(He3))
  - Some MCCD possibilities
  - Lower Hybrid ~2 MW to plasma, ~300 kA I_p drive
- Special diagnostics
  - Unparalleled SOL diagnostics including probes
  - Excellent Thomson including edge Thomson
  - Excellent spectroscopy & bolometry
  - High resolution ECE for Te
  - Phase Contrast Imaging for fluctuations -- but limited radial resolution
  - Long pulse radial DNB: 1.5 sec, 50 keV H^o

Adding geodesic acoustic coupling into Nova-K improves modeling of Alfven cascades

- Alfven cascades (reverse shear Alfven eigenmodes) produced by intense RF heating early in current ramp, when q(r) is reversed with q_{min} = 2.
- Including goedesic acoustic modes raises base mode frequency significantly, yielding excellent agreement with measured frequencies.
- Chirping behavior is sensitive to q(r,t). Agreement with Nova-K indicates these plasmas have reverse shear - potential targets for LH current drive expts.





Porkolab RO3.00006 Edlund KP1.00024

C-Mod Facility Features, cont'd

- Special technical capabilities
  - Gas jet for disruption mitigation
  - Error correction coils for locked-mode threshold studies.
  - Coils to drive damped Alfven eigenmodes
  - Cyro pump for density control (FY07)

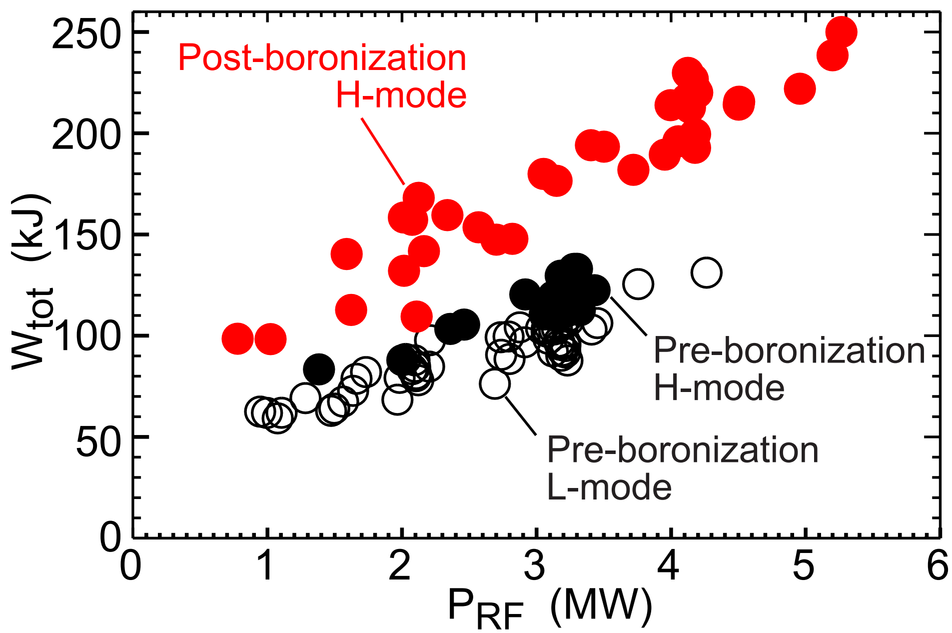
C-Mod Plasmas Features

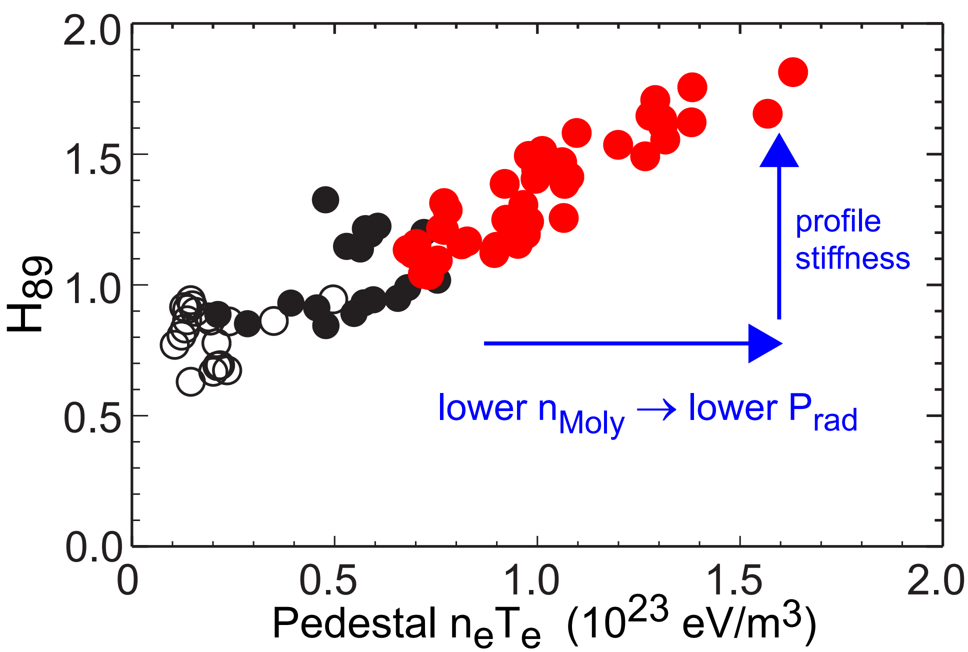
- Plasma regimes
  - 'Enhanced Dα' H-mode … along with other ELMing activity
  - Internal Transport Barrier with off-axis ICRF
  - Lower Hybrid current drive, reverse shear (FY06)
  - Difficult to change q(r) with Ip ramps
  - Plasma shapes: USN, LSN, DN, limited.
  - Typically low β_n → no 2/1, 3/2, 4/3 modes.
- Plasma Parameters
  - B_T = 2 - 8 Tesla, I_p = 0.4 - 2.0 MA, n_e = 0.5 - 6 $\times 10^{20}$, T_{eo} = 1 - 5 keV
  - ~95% of plasmas are 5.4 Tesla, 0.8 - 1.1 MA, 1-2 $\times 10^{20}$, P_{RF} < 4 MW

C-Mod Research Areas

- Lower Hybrid
  - Learn whether control of $n_{||}$ is important.
  - Develop reverse shear and ‘hybrid’ scenarios.
  - Thrust: is LH a promising way to control q(r) in ITER?
- Plasma performance with all-metal walls
  - Will ITER suffer from the reduced plasma performance that we see in C-Mod with all-metal walls?
  - Understanding what makes boronization a good thing.
  - How is the boron ‘used up’?
  - Can intra-shot wall conditioning be developed? Is it extrapolable to ITER?

Extensive Controlled Experiments to Characterize Effects of Boronization





Motivation:

- Overnight boronization since 1996.
- Installed BN tiles in 2000.
- Slow, highly variable loss of τ_E and some difficulty controlling H/D ratio over the years.
- ITER τ_E projections are based mostly on confinement expts with low-Z wall wall coatings (Li, Be, B).

CY 2005 campaign

- Removed boron from PFC
- Removed BN tiles
- Pure metal PFC (Mo)

Overnight vs between-shots boronization

Lipschultz	FI1.00003
Lin	KP1.00002
Hutchinson	RO3.00003
Marmar	RO3.00004

C-Mod Research Areas, cont'd

- Physics of internal transport barrier
  - Controllable with off / on-axis ICRF
  - Its location varies with q_{95}. So LHCD might also provide a useful control knob.
  - Good opportunities for comparison with fluctuations and microturbulence theory.
- Transport & turbulence in Pedestal & SOL
  - Scaling of pedestal & SOL parameters
  - Turbulence, blobs, radial transport to walls.
  - Can we develop a more complete picture of

    Edge flows ←→ rotation ←→ Hmode ←→ theory?
  - Good opportunity here for NSTX comparisons?

Transport near the separatrix may be described in terms of electromagnetic fluid drift 3-D Turbulence

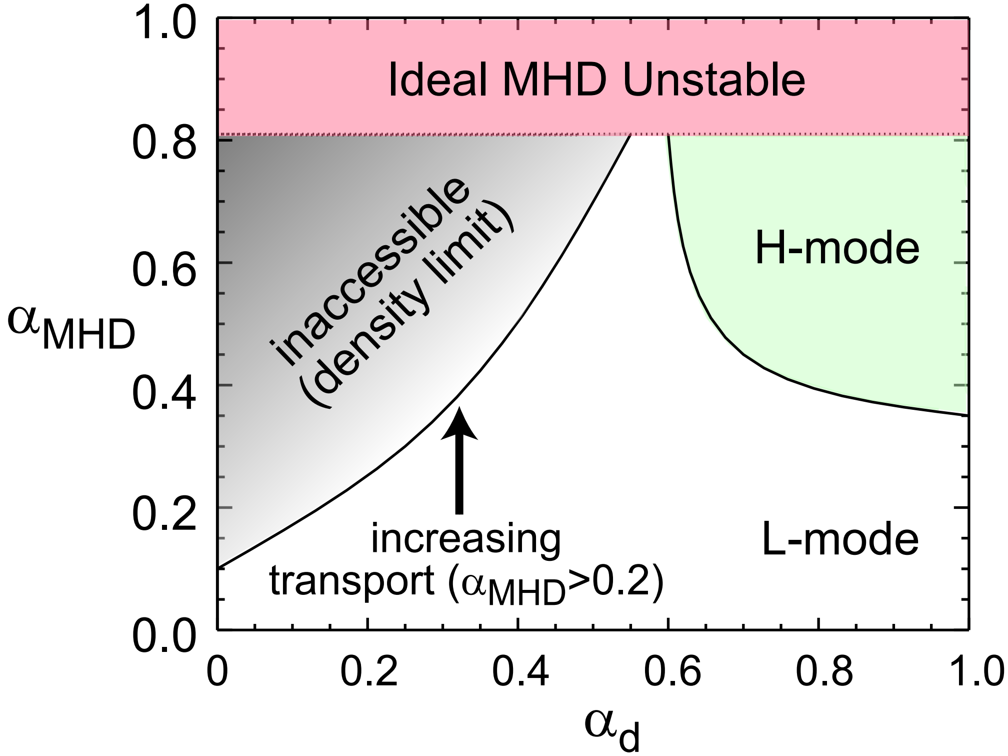
Alcator C-Mod

Turbulence & transport is controlled by two dimensionless parameters

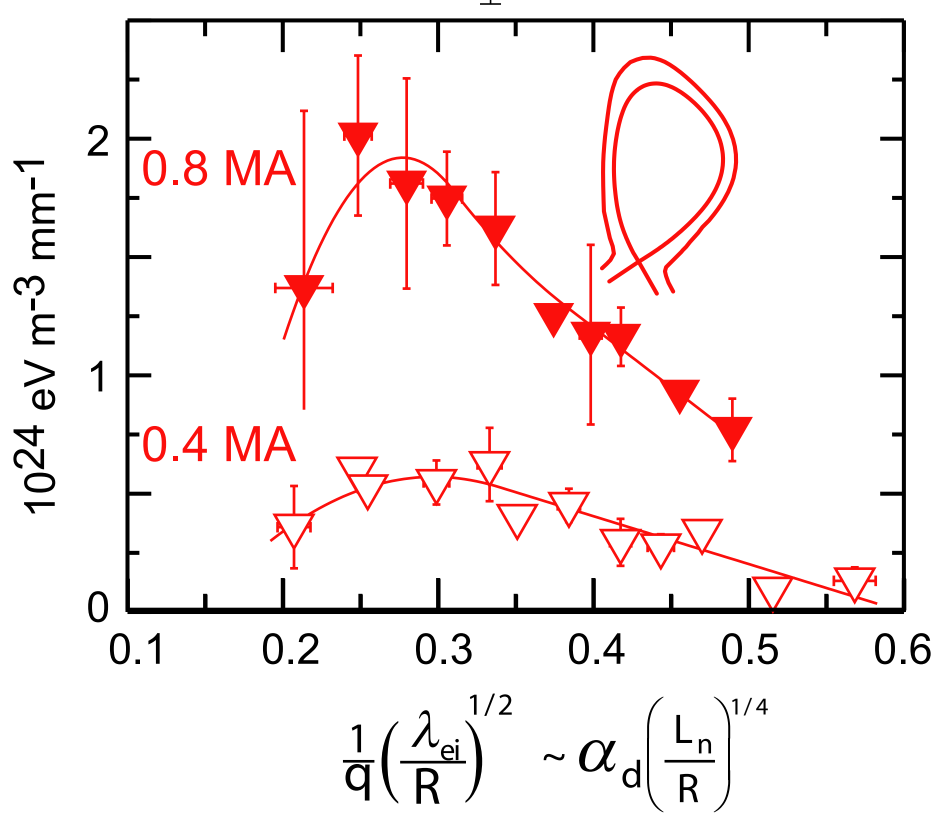
Beta Gradient: $\alpha_{MHD} \propto q^2 R \frac{\nabla_\perp P}{B^2}$ (inverse) Collisionality: $\alpha_d \propto \frac{1}{q}\left(\frac{\lambda_{ei}}{R}\right)^{1/2}\left(\frac{R}{L_n}\right)^{1/4}$

Pressure gradients scale as $\sim I_p^2$.

Transport depends on location in (α_{MHD}, α_d) 'phase-space'



$-\nabla_\perp n_e T_e$

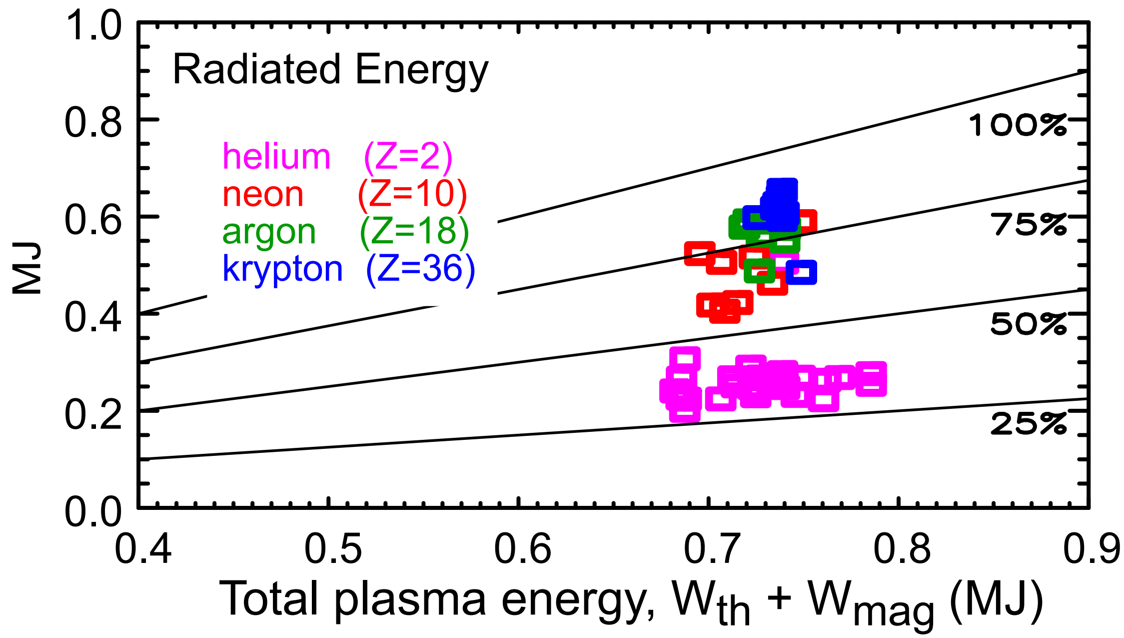


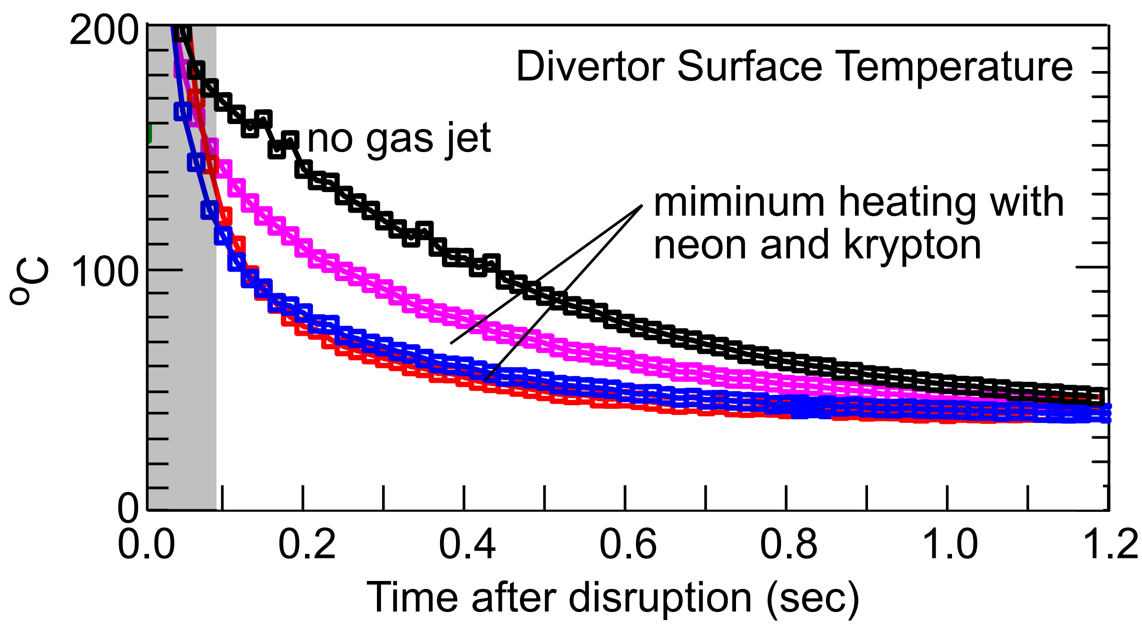
LaBombard RO3.00008

C-Mod Research Areas, cont'd

- MHD
  - Gas jet disruption mitigation
  - Scaling of error fields for locked modes
  - Alfven Eigenmode studies
- Transport & Turbulence
  - Overall focus: role of collisionality & shear on transport
  - χ_e: look for electron modes with PCI ($k < 60\ cm^{-1}$)
  - Particle transport
    - E.g. during ITB.
    - With LHCD, look for Ware pinch effects.

Disruption Mitigation with Gas Jet





- Test efficacy of gas-jet disruption mitigation when P_{plasma}>P_{jet}.
- 10 x higher kinetic energy density and current density than DIII-D, and faster disruption timescale.
- Halo currents reduced up to 50%. Higher Z → bigger reduction.
- NIMROD modeling: T_e collapses, triggers 2/1 and 1/1 MHD, ergodization of field lines, loss of confinement, collapse of core T_e.
- Don't need P_{jet} > P_{plasma} in ITER. MHD provides the 'penetration'.

Granetz LI1b.00001
Izzo KP1.00008
Whyte RO3.00005

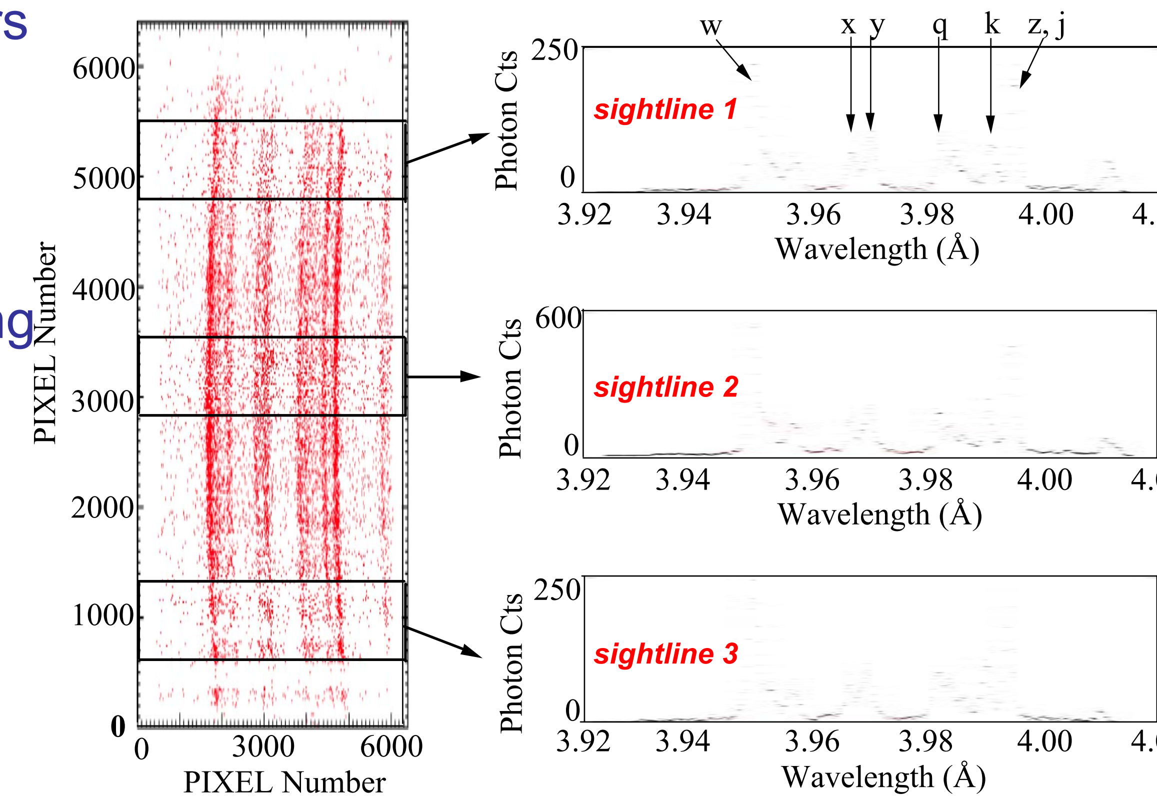
2006 PPPL Collaborators with C-Mod (FTE)

• Lower Hybrid & RF Physics	Bernabei, Wilson, Hosea, Phillips	0.90
• Motional Stark Effect	Scott	1.00
• Curved x-ray crystal spectrometer	Bitter, Hill	0.65
• Correlation reflectometer	Kramer, Kung	0.65
• Gas Puff Imaging	Zweben, Stotler	0.50
• Transport physics, GYRO modeling	Mikkelsen	0.50
• RF & LH engineering support	Brunkhorst, Ellis, Greenough	0.42
• TRANSP support	McCune, Indireschkumar	0.25
• Miscellaneous technical / eng	Guttadora, Gumbas Feder	0.15
	total	~5.0

New X-ray Imaging Crystal Spectrometer

- Consists of a spherically bent crystal and a 2D position-sensitive detector.
- Records spectra of Ar^{16+} from multiple sightlines.
- Measures $T_i(r)$ and $V_\phi(r)$ with spatial resolution ~1 cm, time resolution ~ a few ms with appropriate detector (PILATUS II).
- Concept has been adopted for design of crystal spectrometers on ITER.
- 2006 (base) Test of loaned PILATUS II detector.
- 2007 (incremental) Build, install, operate diagnostic using Ar^{16+} line. $100K hardware.
- 2008 (incremental) Build spectometer viewing Mo line for ITER prototype. $100k hardware.

Spatially resolved X-ray spectra of ArXVII from NSTX



Repair & Upgrades to Correlation Reflectometer

- 2006 baseline program
  - Install replacement 140 GHz Gunn diode for density fluctuation measurements at 2.4 x 10^{20} m^{-3}.
- 2007 baseline program
  - Install 130-140 GHz swept frequency Gunn diode for density correlation measurements.
  - Design ITER prototype correlation reflectometer.
- 2008 incremental program: build, install and operate ITER prototype
  - 180 GHz, X-mode polarization, single channel.
  - Profile measurements using AM modulation technicque using two stable sources close in frequency ($\Delta\nu$ = 50-100 MHz) to obtain group delay.
  - Radial correlation measurements using swept-frequency source ($\Delta\nu$ = 5-10 GHz).
  - Poloidal correlation measurements using poloidally displaced antenna, receiver (no extra source needed).

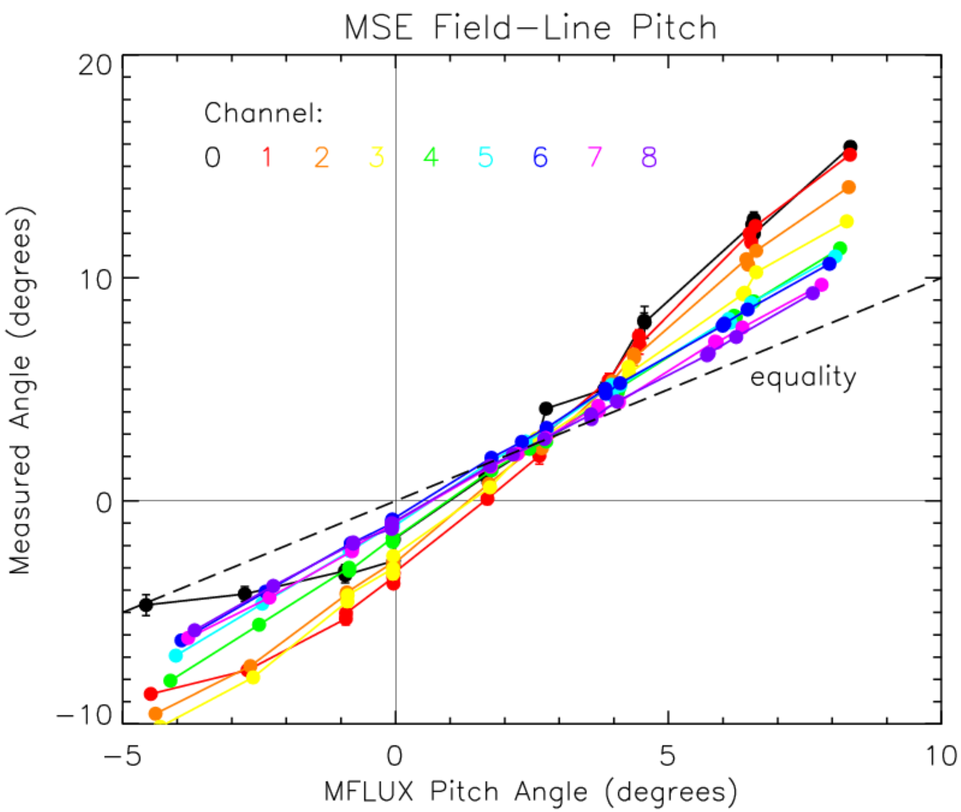
Status and Plans for MSE on C-Mod

PPPL PRINCETON PLASMA PHYSICS LABORATORY

Alcat C-Mo

- Status: diagnostic has not produced q-profiles
  1. Neither calibration technique (beam-into-gas and rotating linear polarizer) reproduces EFIT pitch-angle at plasma edge.
  2. We measure variations of ~several degrees in edge pitch angle among plasmas with the same edge pitch angle as inferred by EFIT.
  3. Extensive calibrations, laboratory measurements and analysis have not yet identified the cause of the calibration and reproducibility problems.
  4. Signal strength has decreased factor 2-10 over the past 18 months.
- Plans
  1. Will test APD detector – should recover lost signal intensity and gain factor 3-4 in quantum efficiency. Might reduce shot/shot variability.
  2. Long-pulse DNB enables new calibration approach: "plasma-jog" that sweeps plasma edge past each MSE channel. Opportunity to bypass possible problems in beam-into-gas and rotating-linear-polarizer calibrations.

Anomalous Features of Beam-into-Gas Calibration



- Apply in-vessel calibration data to beam-into-gas calibration shots.
- Edge channels show significant ‘curvature’ response.
- Slope of measured response is greater than unity for all channels.
- ‘Offset’ exists for all channels.

Diagnostic collaboration opportunities

- MSE & polarimetry
- Correlation reflectometry
- CXRS & BES ?
- 3-chord T_i, V_ϕ, ~25 ms time resolution
- Tight coupling between Ti, Te makes it difficult to separate ion from electron heat flux. An external torque source might make it possible to identify when ion channel improves.
- Diamagnetic loop (currently, it doesn't work)
- Invertable interferometry for density – probably precuded by access limitations.

NSTX Collaborations (Greenwald)

1. Two ITPA-2006 expts involve NSTX and C-Mod:
   - Maingi & Hubbard: small ELM regime comparison [PEP-16]
   - Zweben & Terry: comparison of "blob" characteristics [DSOL-15]
2. X-ray crystal spectrometer (Bitter, Rice)
3. Other ITPA expts involving NSTX – candidates for more active involvement
   - rho* scaling (Kaye, Greenwald, McDonald (AUG) [CDB-8]
   - N-profile at low collisionality: KC Lee, Ernst, Weisen (JET) [CDB-9]
   - ELM structure ans suppressions of NTM (MDC-5): Menard, Wukitch, LaHaye (DIII-D) [PEP-10]
   - Hybrid scenario Kessel, Hubbard, Joffrin (JET) [SSO-2.1]
   - MHD effects on q-profile on hybrid mode: Menard, Hubbard, Buttery (JET) [SSO-2.2]
   - Impact of noise in vertical control in ITER: Gates, ?, Hender (JET) [DIAG-1
   - Tests of diagnostic first mirrors: Skinner, ?, Litnovsky (TEXTOR) [DIAG-2]

NSTX Collaborations (Granetz)

1. Alfven eigenmodes: Snipes, Fredrickson
2. Boronization: Lipschultz, Kugel, Mansfield?
3. Electron transport in low density ohmic rebime: Greenwald, Mazzucato?
4. Self-generated rotation – however, C-Mod just decided to decline ITPA participation.

C-Mod plans for 14 Weeks of Research Operation in FY2006

Alcator C-Mod

- Four weeks accomplished in Fall 2005
- Just completed a short up-to-air (pump-down 1/19/2006)
  - Replaced Faraday Screen on J-port ICRF Antenna
  - Re-installed LH Launcher with stainless steel couplers
- Plasma operation to resume in February, 2006
- Two-three week Plasma Startup & Conditioning period
- Ten week (40 day) research campaign Spring 2006
- Major vent planned for Summer 2006
  - Install cryopump
  - Install W lamellae tile modules
  - Diagnostic upgrades
- Ideas Forum for planning FY07 Experimental Campaign will take place this summer

Fall Campaign (11/01 – 12/06/2005)

Short manned-access vent following FY05 campaign

- Clean up titanium dust in vessel, antennas, internal hardware
- Remove Faraday Screen from J-port antenna
- Cleaning and calibration of accessible in-vessel diagnostic systems

Brief experimental mini-campaign largely devoted to technology issues

- 16 Research Days (beginning 11/04/2005)
- 363 Plasmas
- 12 MiniProposals (2 completed)

ICRF (screenless antenna evaluation)	6.5 days
Wall conditioning	3 days
MHD	1 day
Transport/diagnostic	3.5 days
SOL/divertor	2 days

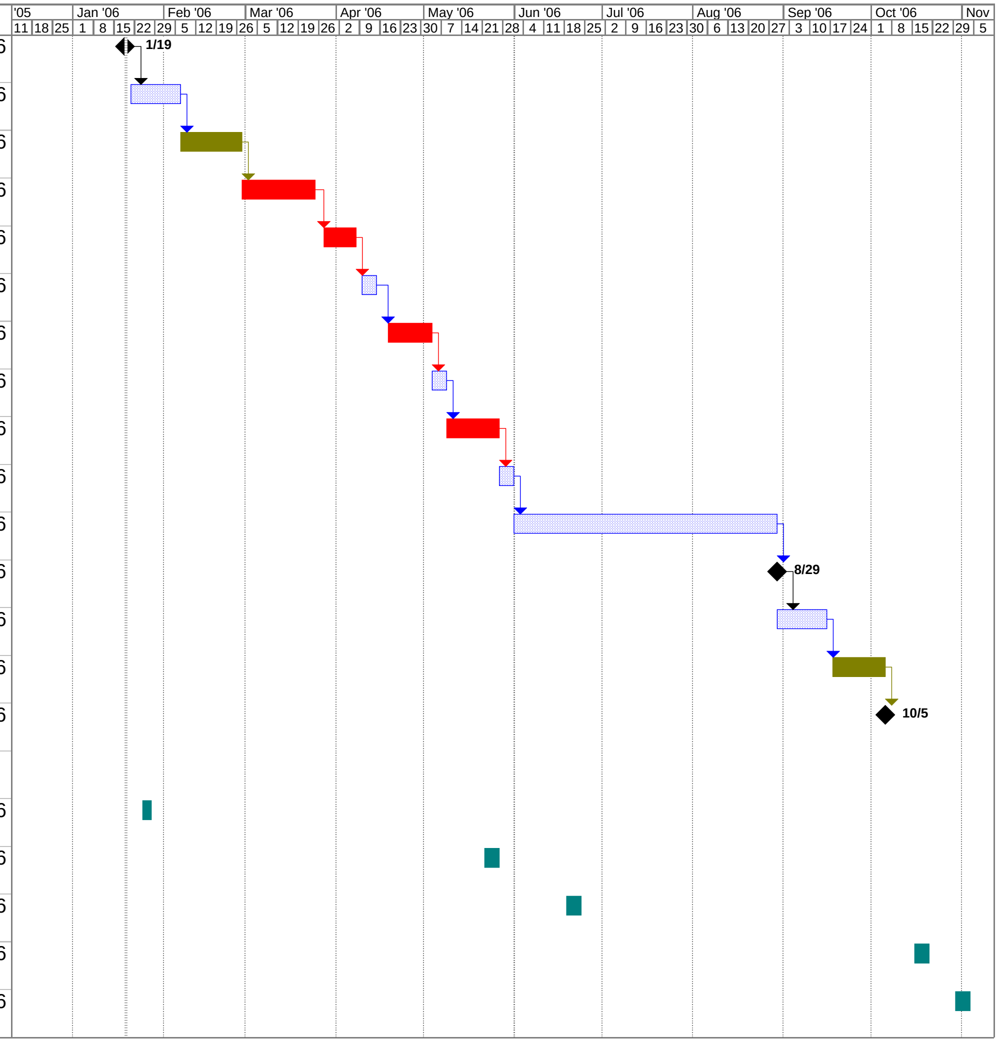
Remainder of 2006 Campaign

- J-port Antenna screen replaced
- Lower Hybrid Launcher re-installed
- Straw-man schedule includes
  - Multi-machine "Joint Experiments" (including ITPA)
  - ITB Physics studies (two-frequency ICRF)
  - Lower Hybrid
  - ICRF Physics studies (including D(He^3) minority heating, MCCD, etc)
  - ITER Integrated Scenario experiments
- Experiments call for a variety of conditions
  - 5-6 weeks with $f_{ICRF} \sim 80$ MHz
  - 1-2 weeks with reversed field, current
  - 2-3 weeks with two-frequency ICRF (70MHz, 80MHz)
  - 1-2 weeks with two-frequency ICRF (50MHz, 80MHz)

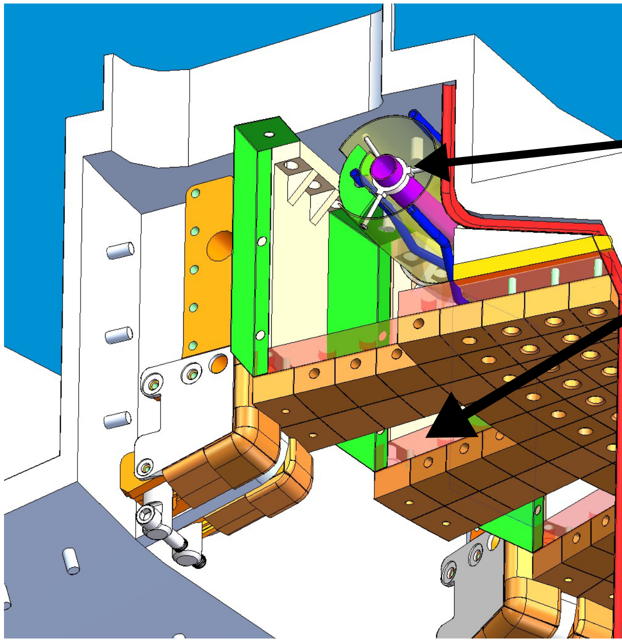
Strawman Schedule for 2006

Alcator C-Mod

ID	Task Name	Duration	Start	Finish
1	pumpdown	0 days	Thu 1/19/06	Thu 1/19/06
2	bake/ecdc	17 days	Sat 1/21/06	Mon 2/6/06
3	plasma condition	14 days	Tue 2/7/06	Mon 2/27/06
4	plasma ops #1 (80 MHz)	16 days	Tue 2/28/06	Fri 3/24/06
5	plasma ops #2 (reversed field)	8 days	Tue 3/28/06	Fri 4/7/06
6	maintenance	5 days	Mon 4/10/06	Fri 4/14/06
7	plasma ops #3 (50 MHz)	9 days	Wed 4/19/06	Wed 5/3/06
8	maintenance	3 days	Thu 5/4/06	Mon 5/8/06
9	plasma opt #4 (70 MHz)	12 days	Tue 5/9/06	Fri 5/26/06
10	warm up machine	5 days	Sat 5/27/06	Wed 5/31/06
11	up-to-air	62 days	Thu 6/1/06	Tue 8/29/06
12	pumpdown	0 days	Tue 8/29/06	Tue 8/29/06
13	bake/ecdc	17 days	Wed 8/30/06	Fri 9/15/06
14	plasma condition	14 days	Mon 9/18/06	Thu 10/5/06
15	Start of FY2007 plasma ops	0 days	Thu 10/5/06	Thu 10/5/06
16				
17	PAC Meeting	3 days	Wed 1/25/06	Fri 1/27/06
18	PSI	5 days	Mon 5/22/06	Fri 5/26/06
19	EPS	5 days	Mon 6/19/06	Fri 6/23/06
20	IAEA	5 days	Mon 10/16/06	Fri 10/20/06
21	APS	5 days	Mon 10/30/06	Fri 11/3/06



FY2006 Hardware Upgrades (January - May)



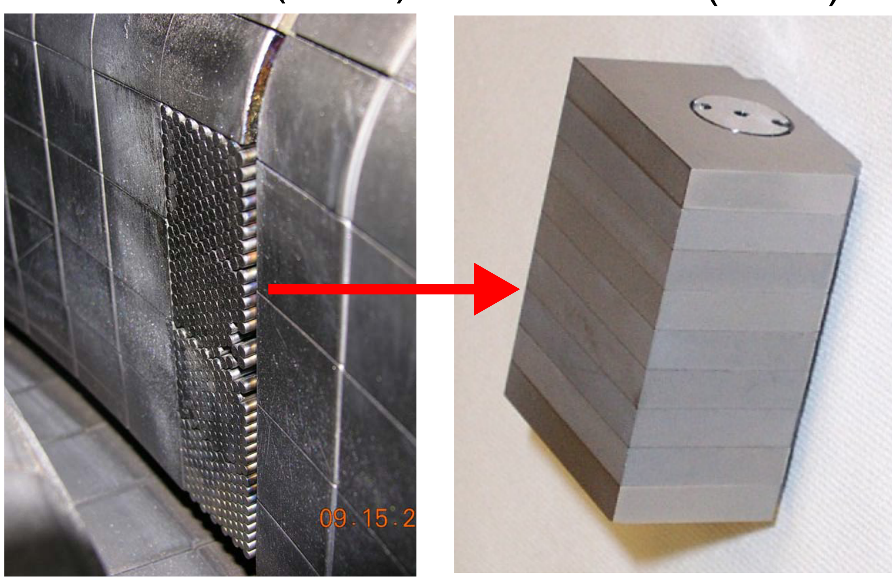
Toroidal cryopump in upper divertor

Liquid helium tube

30 slots in protective hardware provide conductance to cryopump

- Pumping speed: 10^4 liters/s, P_{upper} = 0.4 PA
- Throughput = 10^{21} particles / sec
  $\approx$ 10 x wall outgassing

brush tiles (2005) lamellae (2006)



Tungsten lower divertor

- Laminated W plates, 4mm thick
- Toroidal belt, 1 module high

Resources if you're interested in C-Mod

- me: sscott@pppl.gov, 617-253-8695
- Bitter, Hill, Kramer, Mikkelsen, Phillips, Wilson
- Weekly meetings (usually short!), videoconference, B-205, 4PM Mondays
- C-MOD PAC presentations:
  http://www.psfc.mit.edu/research/alcator/pubs/CMOD_PAC_2006/index.html
- C-MOD mini-proposals:
  http://www.psfc.mit.edu/research/alcator/program/cmod_runs.php?miniproposals=1
- General materials:
  http://www.psfc.mit.edu/research/alcator/pubs/CMOD_PAC_2006/index.html